The realisation of Chipless RFID resonator for multiple physical parameter sensing

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Abstract— We present the design of asymmetric circular split ring resonator as a chipless radio frequency identification (RFID) sensor tag design that can be deployed to measure multiple physical parameters wirelessly in ultra-wideband (UWB) frequencies. Secondarily, the proposed tag design can extend to be used as a chipless RFID tag with actual data encoded for product identification purposes. The proposed resonator design consists of four complementary split circular rings. Each gap between the rings acts as a capacitive sensor which is optimized to have a resonance with a high-quality factor. Each resonance can be considered as a sensor to deploy smart materials that are sensitive to different environmental physical parameters, which can be operated in wireless conditions. The fabricated chipless RFID sensor provides a higher Q factor, aligned with the optimized simulation model. Chipless RFID sensors are comparatively low-cost, but they provide enormous design flexibility in diversified applications. The proposed design holds a great promise for sensing multiple physical parameters in a remote setting.

Keywords—Chipless RFID sensor, Split ring resonator, quasi-static equivalent model, Chipless RFID tag, remote sensing

I. INTRODUCTION

Food waste is a critical concern in the food industry where 20% of all food produced ends up in landfills due to compromise of food freshness and supply chain vulnerabilities. By incorporating technology to detect food freshness, especially for packaged food, smart packaging can play a very important role in reducing food waste [1]. Smart remote sensing using RFID has gained a huge traction in research and industries and the sensors are able to measure the influence of intrinsic and extrinsic factors that can harm food freshness. However, the current RFID-based food freshness sensing technologies are expensive and dependent on a single physical parameter which only provides a one-dimensional view of intrinsic/extrinsic changes taking place inside a food package [2]. A sensing technique which could measure several intrinsic/extrinsic parameters at a single time may help improve the food security at a reduced cost.

Radio frequency identification (RFID) sensor technologies are renowned for their use in detecting and measuring physical parameters in the environment. A chipless RFID sensor generally consists of an RFID tag and a smart material which acts as the sensor element that changes its dielectric properties, for a given physical parameter in the environment. Chipless RFID has been deployed as individual sensors to detect humidity [3], temperature [4], applied pressure [5], pH [6] as well as gas concentration [7]. However, the use of a single chipless RFID sensor for multiple physical parameter sensing has not been thoroughly investigated.

Chipless RFID sensing tags can be designed to resonate in a given frequency band by changing the elements of shape, size, and composition of the tag design [8]. The resonance frequency response is a key element of a chipless RFID sensor as the changes occurring in the induced electrical field can augment the response; hence, it is a valuable tool to determine the sensor performance in microwave frequencies.

Various attempts have been recorded, to develop an integrated sensing platform in the UWB domain. Fletcher suggested a temperature sensor based on ELC resonator [4] and a magnetic material-based chipless RFID temperature sensor [9]. Fletcher also suggested the use of three different layers of magnetic materials which change the magnetic spectrum with temperature. However, the fabrication of such a multi-layer magnetic material-based sensor is considered to be challenging due to the complexity of fabrication; hence, the physical prototype has not yet been realized. Furthermore, a passive surface acoustic wave (SAW)-based RFID temperature and pressure sensor were also presented by W. Buff [10]. In this SAW sensor, a physical or chemical influence changes the propagation characteristics of the SAW sensor, influencing the frequency response of the device. SAW sensor is also considered to be the only commercially available chipless RFID sensor product to date; however, the non-planar behavior and fabrication limitation has restrained it’s wide reach to the mainstream market. Therefore, the realization, as well as the cost of chipless RFID multi-parameter sensors, has not been commercially viable and also the increased complexities restrained the use of sensors in real-world applications.

In this paper, the focus is given to the optimization of chipless RFID sensor design and the RF (Radio frequency) characterization of the tag for multiple resonators with a higher Q factor. The paper further elaborates how each resonator can be used to measure individual environmental parameters in a remote setting. This analysis further emphasizes the design criteria to select split ring resonator as a chipless RFID sensor, the lumped circuit model, and the optimum RF performance of the fabricated resonator.
II. DESIGN CRITERIA FOR CHIPLESS RFID SENSOR

The resonant circuit which is used in chipless RFID sensing comprises of lumped discrete elements such as inductors, resistors, and capacitors. These elements also play a key role in chipless RFID sensing as the lump circuit elements correspond to the surface currents on the tag, induced by the electrical and magnetic fields by the electromagnetic energy transferred through the reader antenna. Smart materials [11] which are inherently sensitive to certain environmental condition (e.g., humidity, temperature) can be used to detect changes in the environment. The selected smart materials trigger changes in its dielectric properties, based on the existence or threshold level of certain environmental condition, which results in a change in resonance frequency response. Such a change will reflect in the frequency response, either a change in amplitude and/or shifting of the frequency response from its original resonance frequency, which can be used to determine the changed behavior of the given physical parameter [12]. Therefore, the selection of appropriate smart materials also plays importance in chipless RFID sensor design.

Split ring resonators (SRR) have also been known as a metamaterial [13], which showcases negative refractive properties [14]. SRR was also used in sensing application [15], due to its symmetrical properties, capacitive behavior and also used in experiments related to wave dispersion, relative permittivity [16] and quality factor measurements [17]. In this paper, the SRR has been selected as the chipless RFID tag architecture, due to SRR’s ability to provide multiple capacitive resonators. Each gap between rings can be used as an independent capacitive sensor. Theoretically, (n) a number of circular rings can allocate (n–1) number of capacitors and this principle was used to develop multiple capacitors in one resonator design. In this paper, the development of four split ring resonator with asymmetric splits and the analysis of the resonator design as a multi-parametric sensor (as shown in Figure 1) are discussed.

![Asymmetric circular four split ring resonator](image)

The mean circumference of any ring resonator should be equal to the integral multiple of the wavelengths. By cutting a split in a closed ring resonator, the total length that is used to excite the whole ring becomes half wavelengths while creating a weak capacitance at the split [18]. In this asymmetric circular split ring resonator (ACiSRR), when the external electrical/magnetic field applies, it generates an electrical field around the rings which induces current on ring’s surfaces. Figure 2 elaborates the excitation mechanism of the chipless RFID sensor using a plane wave and then practical setup to measure return loss (S11) with the patch antenna and vector network analyzer (VNA). Patch antenna acts as a trans-receiver which sends excitation signal and receive it back then shows the S11 through the VNA.

![Chipless RFID Resonator](image)

Figure 2 – (a) Chipless RFID sensor excitation using a plane wave using CST Microwave Studio 2016 (b) Measurement (S11) setup of chipless RFID tag using patch antenna with VNA.

The split stops the current flow across the ring; which helps to create two equal capacitors in both left and right as well as a weak capacitor at the split. On the other hand, the time-varying electrical field can also be able to excite SRR based on the electric charge distribution among half-rings.

![ACiSRR RCS Response (Simulation)](image)

Figure 3 – Simulated RCS response of ACiSRR using CST

Each half ring adjacent to each other acts as two parallel dipoles; hence, they have the ability to induce the current in presence of electric field. Such phenomena lead to cross polarisation effects as the given magnetic field can polarise dipoles electrically and vice-versa; however, a magnetic field is
known to be the dominant excitation mechanism [17]. ACiSRR has multiple transmission lines; hence, multiple modes are generated according to the strip lengths of each microstripline. This phenomenon generates multiple resonances which are elaborated as shown in Figure 3, using its RCS value.

RCS response of ACiSRR in Figure 3 implies that there exist three distinct notches with a higher Q factor at 3.86GHz, 4.6 GHz and 5.75GHz frequencies respectively, which occurs due to the three gaps in between rings. This scenario can be showcased by the analysis of surface currents as shown in Figure 4 (a) below. The highest reflection occurring at the frequencies where the microstrip length is complemented with the corresponding λ/2; therefore, the peaks were recorded at 3.7GHz, 4.35GHz, and 5.3GHz respectively. Figure 4 shows the induced surface current at 3.7GHz when the plane wave was excited as shown in Figure 2 (a). For this analysis, CST microwave studio 2016 was used and field monitors [19] were introduced. Field monitors help to understand the specific electrical and magnetic field behavior on a given frequency.

![Figure 4](Image)

Figure 4 – Surface current at (a) 3.7 GHz (b) 4.35 GHz (c) 5.3GHz

As shown in Figure 4, the resonance characteristics of the SRR are correlated with the surface current concentrations. The maximum surface current density is shown along the gaps between ring resonators (denoted by the red color) and comparatively low current density recorded on top of the microstrip lines. This observation helps to interpret that the higher the reflection coefficient, the lower the concentration of electromagnetic power; hence, the capacitance. Therefore, the concentration of EM power implies the lack of reflection of electromagnetic waves resulting weak attenuation at the receiver’s end. The analyses of the surface current of the ACiSRR provided a cohesive correlation between capacitive properties and surface currents.

![Figure 5](Image)

Figure 5 – ELC Resonator and Spiral resonator designs

From the comparison standpoint, spiral resonator design, as well as popular ELC resonator RF performances, were also analyzed. The main reason (Figure 5 and 6) behind this comparison is to highlight the better Q factor values produced by the ACiSRR in contrast to other resonators.

![Figure 6](Image)

Figure 6 – RCS response of ELC resonator vs Spiral resonator vs SRR (ACiSRR)

As visually explained in Figure 6, SRR (ACiSRR) stands better in contrast to Q factor as well as RCS value. ELC has very low RCS which may due to the smaller size as well as thinner widths of the microstrip lines. Each line in the spiral resonator are continuous hence unable to make multiple resonances; however, it shows better Q factor in contrast to ELC resonator. However, SRR still has better performances when comparing with the RCS values of spiral resonator.

Apart from its RF performances, the proposed ACiSRR tag also considers the following key factors in UWB frequency such as simplicity, low-cost, robustness and scalability. Especially when it comes to food safety, the proposed sensor may have the potential to measure multiple parameters which are key freshness indicators in perishable food products such as humidity, temperature, and pH.

III. INVESTIGATION OF SMART MATERIALS AND ANALYSIS OF CHIPLESS RFID SENSOR BEHAVIOUR

As proposed in the previous section, the suggested ACiSRR design is capable of generating 3 notches where each notch acts as a capacitive sensor. In the food safety applications, where humidity, temperature, and pH measurements are key to guarantying the food quality [20, 21] as extrinsic measures (Figure 7), the following suggestions were made.

- Environment condition – As the plan was to measure food safety using the proposed sensor the following parameters with thresholds in Table 1 were established.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity</td>
<td>20% to 100%</td>
</tr>
<tr>
<td>Temperature</td>
<td>4°C to room temperature</td>
</tr>
<tr>
<td>pH</td>
<td>4 to 7</td>
</tr>
</tbody>
</table>

As per Table 1, if the sensor exposes to room temperature the dielectric constant of the rGO changes; hence, it resulting in a change in permittivity [16] which eventually impacts the frequency response. Similar scenarios can be applied to humidity and pH measurements as well.

- Selection of smart material – Three distinct graphene compounds were selected and their respective dielectric properties were elaborated in Table 2.
Graphene oxide [22] for humidity sensing
- Reduced graphene oxide for temperature sensing
- Chitosan with graphene oxide for pH sensing

In the analysis of permittivity [16], it is important to understand the measurement of permittivity, and the free space method is considered to be more promising as a method of measurement of permittivity in a remote sensing setting.

**Complex Permittivity** ($\varepsilon$) = $\varepsilon' - j\varepsilon''$

- $\varepsilon$ – Relative complex permittivity
- $\varepsilon'$ – Relative real permittivity (Dielectric constant)
- $\varepsilon''$ – Relative imaginary permittivity

It is also equally important to recognize that the deriving of the values of dielectric constants and loss tangents are subjected to change based on the preparation method of the smart material. As an example, GO can vary its dielectric constant substantially based on its preparation method. The values mentioned in **Table 2**, some of which were derived from theoretical models as well as from prior experiments conducted with specific smart materials. Thereafter, these modelled values were implemented to the CST simulation model, where the respective smart materials were deployed into the capacitive gaps (between rings and split) of ACiSRR and then analyzed using their respective frequency responses.

In the initial sensitivity analysis, GO was deployed in between the outermost ring and second ring. Thereafter, the sensor was excited by a plane wave (Figure 2(a)) and then changed the dielectric property of the GO from 12 to 16, and loss tangent 0.25 to 0.4 respectively and RCS responses were obtained as shown in Figure 8.

In Figure 8, a clear frequency shift in all resonances can be observed; however, a significant shift (from 3.86GHz to 3.26GHz) was recorded of the resonance where the smart material (GO) was deployed. This concludes that the capacitance has been significantly changed by the deployment of smart material in between rings. In this analysis, the capacitance generated by the split gap has considered negligible over the overall capacitance of the ACiSRR.

**Table 2 – Smart materials and dielectric properties**

<table>
<thead>
<tr>
<th>Smart material</th>
<th>Measurement range</th>
<th>Dielectric constant in microwave frequencies</th>
<th>Loss tangent in microwave frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene oxide (GO)</td>
<td>20% to100%</td>
<td>12 to 16 [23]</td>
<td>0.25 to 0.4 [24]</td>
</tr>
<tr>
<td>Reduced graphene oxide (rGO)</td>
<td>4°C to room temperature</td>
<td>6.4 to 3.2 [25]</td>
<td>0.4 to 0.8</td>
</tr>
<tr>
<td>Chitosan</td>
<td>7 to 4</td>
<td>6 to 4 [26]</td>
<td>0.04 to 0.02</td>
</tr>
</tbody>
</table>

In this scenario, GO was deployed to the model to understand the baseline of the sensor prior to exposure to the different environmental condition as shown in Figure 9. In this scenario, GO was deployed to the outermost gap and chitosan deployed to the most inner gap between rings.

As shown in Figure 9, the simulation results showcase that the deployed smart material has been made a significant shift in the frequency response to the left. The most likely reason for such a frequency shift is the increase in material capacitance between rings, which has increased the dielectric constant. Such an increase in dielectric constant also increases the overall insulation properties of the ACiSRR.

Similarly, both rGO and Chitosan materials were also along with GO deployed to the model to understand the baseline of the sensor prior to exposure to the different environmental condition as shown in **Figure 9**. In this scenario, GO was deployed to the outermost gap and chitosan deployed to the most inner gap between rings.

As shown in Figure 9, the simulation results showcase that the deployed smart material has been made a significant shift in the frequency response to the left. The most likely reason for such a frequency shift is the increase in material capacitance between rings, which has increased the dielectric constant. Such an increase in dielectric constant also increases the overall insulation properties of the ACiSRR.

Thereafter, changes in dielectric constant and loss tangent were incorporated into the simulation model and similar approach was followed for all three materials. Finally, the overall change in the RCS response was recorded as shown in **Figure 10**. As per Figure 10, it can be seen that the humidity sensor further reduces its amplitude and shift to the left due to the increased dielectric properties. Due to this reason, the overall insulation property increases as well. On the other hand, both rGO and chitosan enhance their conductive properties by shifting to the right. Moreover, reduction of loss tangent also

**Figure 7 – Key freshness factors in perishable food items**

**Figure 8 – Simulated frequency domain response with sensing material (Graphene oxide) between outer and second ring**

**Figure 9 – Simulated frequency response of ACiSRR with and without smart materials GO, rGO and chitosan with dielectric constants 12, 6.4 and 6 respectively**
The development of the ideal theoretical model does not justify the real world environment; hence, further analysis has carried out to implement quality factors into each lump element as shown in Figure 12. The optimum quality factors values were obtained using the simulations and tuning functions available in the ADS modeling software. Considering the lump values and the quality factors, the S11 parameter was obtained as shown in Figure 13.

![Figure 13 – The theoretical S parameter plot using ADS](advanced-design-systems-from-keysight-technologies.png)

As per Figure 13, the theoretical values along with quality factors have shifted all three resonances to the left. However, towards the higher frequencies, the shift has minimized. The likely reason for such phenomena is the lower quality factors in inductors and capacitors in outer rings with respect to higher quality factors in the inner rings of the ACiSRR design.

In the development of the theoretical model, the basis of split resonator where the split gap divides the ring capacitance into two equal capacitors (distributed capacitance) was considered [28]. The overall length of the resonator considered for the total inductance of the LC model [29]. In general, SRR when two rings are excited in their fundamental mode, the distributed capacitance in one half is in series with the other half based on their current and voltage distributions. Therefore, every two rings represented two series capacitance while adjacent rings create parallel capacitance. These established hypotheses were used in developing the LC model as elaborated in Figure 11 and 12. The mutual inductance between parallel stems and the mutual capacitance among non-adjacent rings were excluded in the current model to keep the LC model simple.

The model explained in Figure 11, used several equations listed below in order to come up with respective inductance and capacitive values for the LC model.

**Total Inductance** ($L_T$) = \( \frac{\mu_0}{2} \frac{l_{avg}}{\pi} \ln \left( \frac{0.998}{\rho} \right) + 1.84\rho \)

In Eq (1), $L_T$ stands for total inductance where $\mu_0$ is the vacuum permeability, and $l_{avg}$ is the average strip length which can be calculated using the below equations [30].

\[
l_{avg} = 4[1 - (N - 1)(w + s)]
\]

where $w$ is the width of the strips and $s$ is the gap between rings. $N$ stands for the number of rings where N=4 in this particular ACiSRR design. $\rho$ stands for the filling ratio as elaborated in Eq (3) [29].

\[
\rho = \frac{(N - 1)(w + s)}{[1 - (N - 1)(w + s)]}
\]
Finally, the total inductance was calculated as 4.72nH. Moreover, equation (4) to (8) were used to calculate the total capacitance of the LC model.

\[ C_T = \frac{(C_1+g_{ap})(C_2+g_{ap})}{(C_1+g_{ap})(C_2+g_{ap})} \] (4)

Where \( C_T \) denotes the total capacitance of the two capacitors in series and \( g_{ap} \) provides the capacitance of each split gap. A similar approach can be used to calculate the capacitance of other series branches for \( C_3, C_4 \) and \( C_5, C_6 \). Each capacitance above (except split gap) can be calculated using the following equation (5). In this calculation, per unit length capacitance between two parallel strips was considered.

\[ C_n = \varepsilon_0 \frac{K(\sqrt{1-k^2})}{K(k)} \] (5)

Where \( k \) stands for the elliptic integral of the first kind and \( \varepsilon_0 \) for the relative permittivity of air. The value for \( k \) can be found using equation (6).

\[ k = \frac{s}{w + \frac{s}{2}} \] (6)

The capacitance of the split gap can be calculated as in equation (9), where \( g \) stands for the split gap distance. The value of \( g \) varies among each ring resonator which results in different capacitive values. The surface area of each ring is calculated using \( w \) (width of the strip) and the height of the conductive layer (\( h \)).

\[ g_{ap} = \frac{\varepsilon_0 w h}{g} \] (7)

Once all the gap capacitors and the capacitance between each ring resonator is calculated, the total capacitance can be calculated as,

\[ C_{total} = C_{r1} + C_{r2} + C_{r3} \] (8)

These \( C_{r1}, C_{r2}, C_{r3} \) were used along with calculated inductance to develop LC model in ADS (Advanced design system) software to verify the resonance frequencies as shown in Figure 10 (a). The relationship between LC and resonance frequencies of a LC model can be calculated using the below equation (9).

\[ \text{Resonant Frequency} (f_0) = \frac{1}{2\pi} \frac{1}{\text{LC}_T} \] (9)

The derived resonance as in Figure 12, are well aligned with the frequencies obtained from the simulation, which concludes that the LC circuit model is aligned with the ACISRR chipless sensor design.

This can be explained that the ADS model represents the ideal scenario where ideal inductance and capacitors were used to calculate frequency resonances. There are more factors to be considered such as resistivity of the elements, dielectric losses which were not represented in the theoretical model. However, resonance frequencies provide a closer approximation in both simulation and the theoretical model. The analysis of the ACISRR chipless sensor tag in CST simulations for its multiple mode resonances and the LC model derived from theoretical calculations have provided an established foundation of the ACISRR tag’s expected RF performance. It can also conclude that multiple smart materials can be deployed into the ACISRR sensor design which is useful for single or multiple physical parameter sensing applications. These proposed sensors are useful for food safety application as elaborated in section 3. The interesting alignment of such smart materials can also be deployed for other sensor-based applications such as gas sensing, air quality monitoring, precision agriculture, health care and wellbeing, which further emphasizes the usefulness of this microwave resonator design.

Following all above analysis, the promising performances of the ACISRR sensor design obtained from simulation models have helped to make a decision to fabricate the sensor and measure tag’s RF measurements as elaborated in the next section.

V. FABRICATED PERFORMANCE ANALYSIS

The ACISRR sensor tag was developed using Taconic-TLX8 [31] substrate which has low loss tangent in comparison to other Teflon based dielectric substrates. The properties of the substrate used are elaborated in Table 4. Low loss tangent \( (\tan \delta) \) is useful in sensor development in order to achieve a high Q factor in S11 measurements. Thereafter, the ACISRR Tag was fabricated and return loss \( (S11) \) measurements were taken as shown in Figure 15 (a) and (b) respectively. To measure the performance of the CSRR tag, a single patch antenna was used (as elaborated in Figure 2(b)) in a laboratory environment using a VNA. In the calibration of the chipless RFID tag in the measurement environment, we consider that a single antenna will act as both transmitter and receiver as shown in Figure 2 (b). Moreover, as the different resonators in the ACISRR resonate at distinct frequencies, the transmitted interrogated pulse from the patch antenna is immediately reflected from the tag, another part of the substrate as well as from the other objects in the environment. The total received signal can be modeled by considering the following formula.

\[ \text{Total received Signal} (Y_r) = Y_r + Y_s + Y_a \] (10)

In this \( Y_r, Y_s \) and \( Y_a \) stand for, the return loss profile of the antenna, structural mode RCS and antenna mode RCS respectively [32]. The \( Y_r \) component will gradually become redundant once the transmission is completed as there is no reflection due to return loss. It is also to note that, the presence of a tag in front of the antenna has slightly changed the original S11 measurement of the antenna as the S11 is now influenced.
by the backscattered incident from the tag. Therefore, the antenna can now be considered as loaded by the chipless RFID tag and can denote using below formula.

\[ Y(t) = F^{-1}[S11_{\text{loaded}}(f)X(f)] \quad (11) \]

And from equation (11), now we can derive the actual reflection by the tag as follows.

\[ Y_s + Y_a = F^{-1}[S11_{\text{loaded}}(f) - S11(f)X(f)] \quad (12) \]

This understanding is used to calibrate the tag against the antenna or the same principle applies when considering S11 measurements with tag and without the presence of the tag as follows.

\[ Y_s + Y_a = F^{-1}[S11_{\text{with tag}}(f) - (S11_{\text{without tag}}(f))X(f)] \quad (13) \]

In the actual measurements, the measured antenna S11 (loaded with tag) from the setup shown in Figure 14 was the plot against the RCS value obtained from CST microwave studio simulation model. The distance between the patch antenna and the fabricated tag kept 3cm; however, same performance can be maintained even at 10-15cm when we use comparatively larger tag size. The understanding of reading range can be further explained using the radar range equation [33] as follows.

\[ P_{\text{tag}} = L_{\text{ Dịch}}[(1 - \Gamma^2) \times \frac{\epsilon_r D_{\text{ant}}^2 \lambda^2}{4\pi R^2}] \quad (14) \]

Where, \( L_{\text{ Dịch}} \), \( P_{\text{src}} \) and \( \Gamma \) stands for coupler loss in the antenna, transmitted power at the source and complex reflection coefficient respectively. Additionally, \( \sigma_{\text{tag}}, D_{\text{ant}}, \epsilon_r, \lambda \) and \( R \) stand for RCS of the chipless RFID tag, Antenna directivity, radiation loss of the antenna, the wavelength and most importantly the distance between the antenna and the tag. As it shows in the equation, power received by tag reduces drastically when the distance increases, unless the increase in source power. When the power received by the tag reduces, it impacts the signal which is backscattered, hence the amplitude levels of the S11 measurement. In this measurement, the reading range can easily be increased up to 10cm as the RCS value obtained from the simulations accounted 10cm as the distance between the tag and the antenna. However, the inherent fabrication errors and the loss factors have shifted the tag response as per Figure 15 (b) which can even shift further upon the use of smart materials for sensing. In such a case, there is a chance that shifted resonances may overlap each other due to the shift which needs to be avoided in practical use. This is the main reason to keep tag close to the patch antenna in this experiment.

<table>
<thead>
<tr>
<th>Table 4 – Taconic-TLX8 substrate material properties</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material Properties</strong></td>
</tr>
<tr>
<td>Substrate Thickness</td>
</tr>
<tr>
<td>Dielectric Constant</td>
</tr>
<tr>
<td>Loss Tangent</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
</tr>
</tbody>
</table>

As observed in Figure 15, the resonances appeared in the measured frequency response are slightly shifted in comparison to the RCS response. However, it can also observe that the Q factor has reduced in the measured response in contrast to the simulated frequency response. A possible reason for such an outcome can be the fabrication errors and minor unevenness in the Taconic substrate itself. It has also been seen that the amplitude level has reduced in the S11 measurement. However, the resonances are clearly visible; hence, the outcome can be measured without deploying advanced signal processing techniques.

There may be an argument can be made, the key similarity of RCS and S11 (Reflection coefficients) measurements according to Figure 15. It can be considered as similar when it comes to the chipless RFID backscattering principle. The RCS was calculated using the amount of reflection that the conductive elements of the chipless RFID can reflect back to the source using a plane wave excitation mechanism. In such a scenario, the total incident power transmitted is calculated against the power scattered through the unit angle reflection as the RCS. This phenomenon is prominent when it comes to the far field as the self-interference from the electric field has a minimum impact over the transmitted/reflected electric field. This understanding has helped to elaborate reflection coefficient in the actual measurement and its correlation RCS. The definition of return
loss is hypothetically equal to the reflection coefficient [34]. The return loss is the reflected scattering power which is similar to RCS when it comes to reflection per given unit length/direction. Therefore it can be reasonably assumed that RCS and S11 are same when it comes to remote measurements given the consideration that both recognized as far-field measurements.

In order to get rid of noise clutter, a further assumption is taken that in both simulation and S11 measurements, clutter remains as statistically independent. The simulation model itself model the noise level in the environment given the dielectric values and loss factors of the environment and tag materials which are actually used in the measurements in real life scenario. The reading distance which is also proportional to the noise (far the distance, the lesser the reflection comes back to the source) is also considered in the simulation model as if in the real measurements. This is one of the reasons the RCS value comes very close to S11 measurements; however, there is always an error factor which can cause certain deviations. This error may happen due to the undesirable environmental reflections beyond the simulation model and also happen due to the fabrication errors.

Moreover, the analytical calculations are carried out to support the limitation exist in the chipless RFID reading system elaborating the key parameters used in this measurement according to the Friss free space equation [35] as follows.

$$\text{Reading range } (R) = \left( \frac{G_T G_R \lambda^2 P_T}{(4\pi)^3 P_R} \sigma \right)^{1/4}$$

Where the GT, GR stands for the gain of the transmitting and receiver antenna and it is 6dBi as the same patch antenna is used as a trans-receiver. The wavelength considered for the frequency of 5GHz and PT the transmitted power of the antenna is 0dBm according to the FCC regulations [36]. PR value is considered as -50dBm based on the sensitivity of the receiver antenna which can certainly be improved by using a horn antenna which has a higher sensitivity. Horn antenna usually has a higher gain, thus increases the efficiency of the power transmitted to the tag antenna which may also increase the ability to get a higher reflection back to the receiver. The noise level of the measurement setup was -60dBm. For example, use of a horn antenna increases the reading range almost twice as the current reading distance; however, the main expectation of this experiment is to use practical experimentation model that supports the truly wireless nature of the tag when it’s used as a chipless RFID sensor in the real world. Furthermore, RCS ($\sigma$) value of the tag is 625mm$^2$ as the main intention of the tag development is to keep the tag size as small as possible to lower the cost of the tag as possible. The increased tag size will certainly increase the conducting surface areas which help to achieve higher reading range. Path loss (4$n$) is also considered in this calculation. By inputing all the above values, it was found that the maximum reading range of the antenna is approximately 8cm. The frequency sweep is used as the interrogation signal throughout the experiment. There are some other approaches is also available to provide different approaches to find read range when using multiple antennas and [37, 38]; however, the current use of Friss free space equation provides a more suitable theoretical approximation to the measurement setup.

The few more measurements were taken to validate the reading range and following S11 responses were obtained as in Figure 16. As it can be seen that even at the 10cm distance the three resonances are clearly visible irrespective of the changes in the amplitude levels and frequency shifts.

$$\text{Figure 16 – S11 measurements in various read range}$$

The increasing distance also increases the background reflection. In an ideal event only the amplitude should get decrease with the increased distance; however, in practical measurement notches can also shift due to the changing dielectric properties of the environment as this is not a closed system during measurements and not additional steps taken (eg: foam to absorb noise) to reduce noise as this should mimic the real world measurements. Moreover, the near field and far filed distances are also calculated [39] using the antenna dimensions (3cm diameter) and it is safe to assume that these measurements are considered as far-field measurements. Far-field measurement comes to 3cm which is the exact distance that is used for the measurements of the chipless RFID tag.

$$\text{Figure 17 – Simulated RCS response of five ring vs ACiSRR chipless RFID sensor tag (Taconic-TLX8)}$$

Furthermore, as shown in Figure 17, another simulation was carried out to see the performances of the chipless RFID tag design, when one more ring added to the design. The reason behind such model development is to understand the system capacitance when more and more rings added to the design.

As per Figure 17, it is clearly visible that the amplitude has reduced in the RCS response has reduced when more rings added and alternatively, four resonances (instead of three) occurred in the same bandwidth. Having resonances
closer to each other may develop some sensitivity concerns when this five-ring design is used as a sensor, as the resonances may move and overlap with the deployment of smart materials. But with additional microstrip ring added, more capacitance is added to the system as a parallel capacitor. This scenario enables, the use five ring (or more) SRR as a potential chipless RFID sensor with more sensing elements. It is also recommended to investigate other low-cost substrates and fabrication techniques such as Screen printing [40] in order to understand the commercial potential. Taconic-TLX8 is one of the most expensive printed circuit board (PCB) substrates in the market. Screen printing is one of the known techniques that are currently in use in developing low-cost chipless RFID tags. In printing, the performance of tag is heavily dependent on the conductivity of the printing substrate as well as the substrate used as the carrier. The printed tag provides not only a cheaper alternative but also more flexibility which is helpful in the diversified application where the bendability/pliability is demanded, which is important in food safety applications. The performance of printed chipless RFID sensor can also be affected by the fabrication errors, impurities in ink mixture, measurement errors (effect of the environment eg: higher humidity).

Finally, the resolution of tag response has been taken as part of the overall performance analysis. Usually, the resolution of a tag can be denoted by its Q factor (Quality factor). As per the simulation of the RCS value (Figure 3) and measured S11 (Figure 13), the Q factors [41] of three notches can be calculated as below in Table 5.

<table>
<thead>
<tr>
<th>Table 5 – Calculated Q factor values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>3.86</td>
</tr>
<tr>
<td>4.6</td>
</tr>
<tr>
<td>5.75</td>
</tr>
</tbody>
</table>

$$Q = \frac{\text{Notch Frequency}}{f_1 - f_2} \quad (10)$$

It can be clearly observed that the Q factor has changed significantly from simulation RCS to the measured S11. However, towards higher frequencies, the difference of Q factor has been reduced significantly. Moreover, the frequencies also shifted by approximately 100-150MHz which may happen due to the fabrication errors as well as form the noise from the environment during the backscattering process. The use of a single patch antenna where the innermost ring provides most of the reflection can be a reason for obtaining similar Q factor in contrast to simulation Q factor values. This can be further explained by considering the beam pattern of the single patch antenna where directivity of the main lobe more aligns with the innermost ring. Nevertheless, measured S11 provides the evidence of higher quality factor of resonances. The overall error between simulation and measured results can be summarized in Table 6. This table further emphasizes that variation of Q factor as explained above; however, in terms of amplitude variation resonance at 4.6GHz is closer to simulation RCS value in comparison to other two resonances.

By all these analyses from the surface currents, RCS value, Q factor (resolution), simulation models as well as the fabricated performances, it can be reasonably concluded that,

- Circular split ring resonators are suitable to be used as an integrated sensing platform due to,
  - Its higher RCS
  - Higher Q factor.
- The increase of a number of rings will add more capacitance to the sensor system. However, careful consideration is necessary to maintain a higher RCS and higher Q value to be used as a chipless RFID platform.

**VI. CONCLUSION**

In this paper, we have presented the design of chipless RFID resonator tag design suitable for employing multiple smart materials as sensing media. Particularly, we have detailed out the design rationale, a quasi-static model of the suggested design, capacitive properties, analysis of surface currents, tag resolution, theoretical modeling and more importantly comparison of fabricated performances using both PCB and screen printed techniques. Finally, the results of this analysis can be used to design a tag with higher data bits, which is useful in multi-physical parameter sensing or as a tag ID for product identification purposes.

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